



Space Weather impacts on satellites at different orbits



Outline

- ✓ Intro of man-made satellites
- ✓ Orbits
- ✓ Different types of SWx effects on satellites
- ✓ Satellite anomalies from the recent March 2012 SWx events

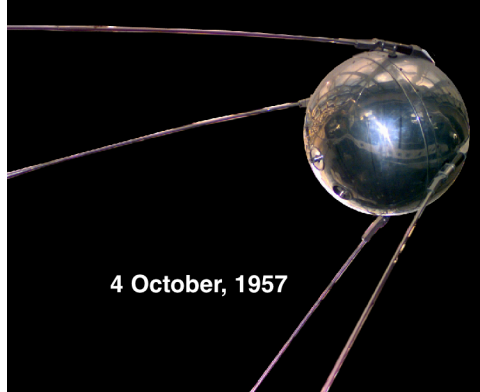
Yihua Zheng
Feb 25, 2015

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Growing reliance on space technology



1st Satellite Launched Into Space



The world's first artificial satellite, the **Sputnik 1**, was launched by the Soviet Union in 1957.

marking the start of the Space Age

International Geophysical Year: 1957



Space dog - Laika



the occupant of the Soviet spacecraft Sputnik 2 that was launched into outer space on
November 3, 1957



Paving the way for human missions

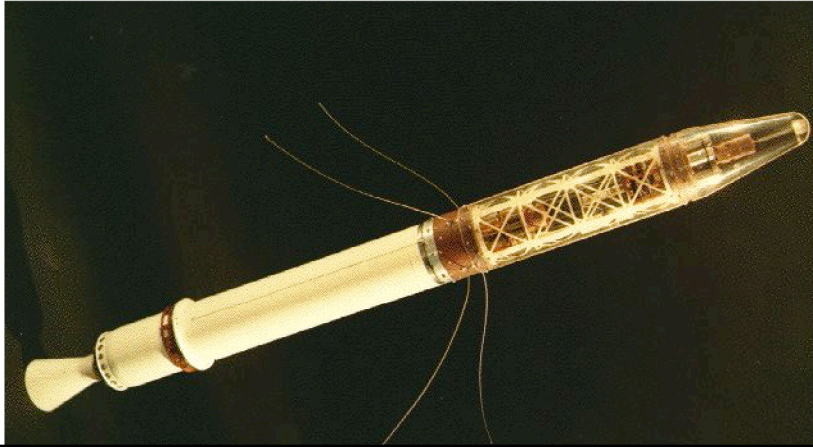
3

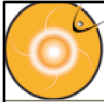


Explorer I – 1st U.S. Satellite

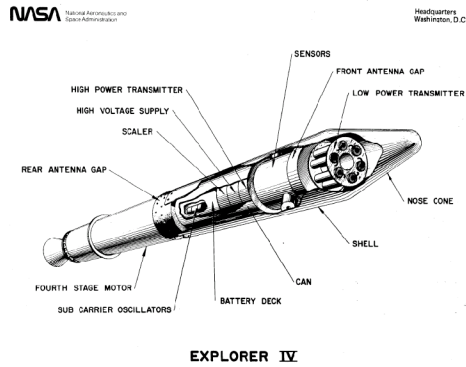


- Explorer 1, was launched into Earth's orbit on a Jupiter C missile from Cape Canaveral, Florida, on January 31, 1958





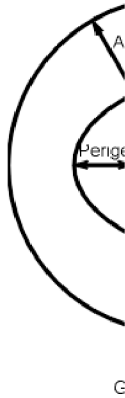
Discovery of the Outer Van Allen RB



Pioneer 3 (launched 6 December 1958) and Explorer IV (launched July 26, 1958) both carried instruments designed and built by Dr. Van Allen. These spacecraft provided Van Allen additional data that led to discovery of a second radiation belt



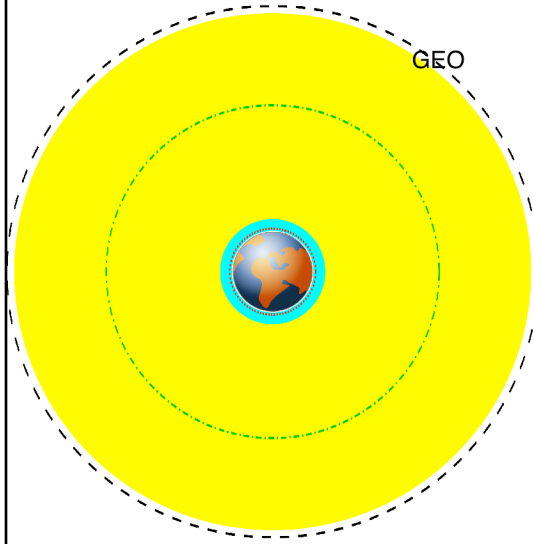
Orbits



ORBIT NAME	ORBIT INITIALS	ORBIT ALTITUDE (KM ABOVE EARTH'S SURFACE)	DETAILS / COMMENTS
Low Earth Orbit	LEO	200 – 1200	
Medium Earth Orbit	MEO	1200 – 35790	
Geosynchronous Orbit	GSO	35790	Orbits once a day, but not necessarily in the same direction as the rotation of the Earth – not necessarily stationary
Geostationary Orbit	GEO	35790	Orbits once a day and moves in the same direction as the Earth and therefore appears stationary above the same point on the Earth's surface. Can only be above the Equator.
High Earth Orbit	HEO	Above 35790	



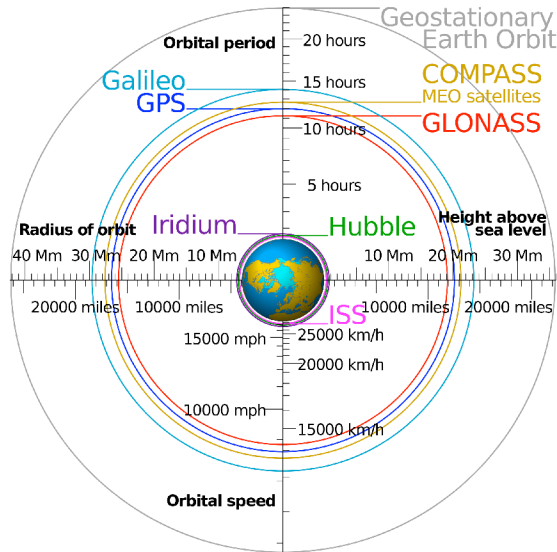
Orbits



Yellow: MEO
Green-dash-dotted line: GPS
Cyan: LEO
Red dotted line: ISS



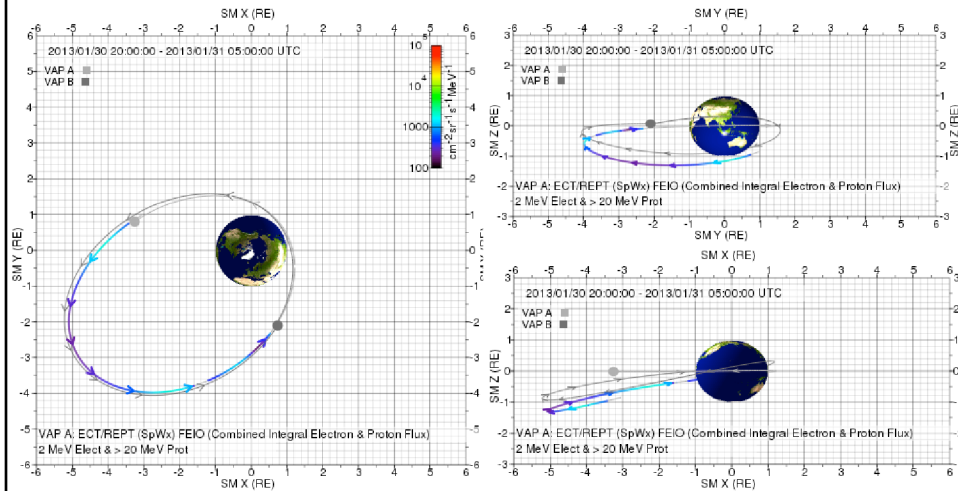
Orbits



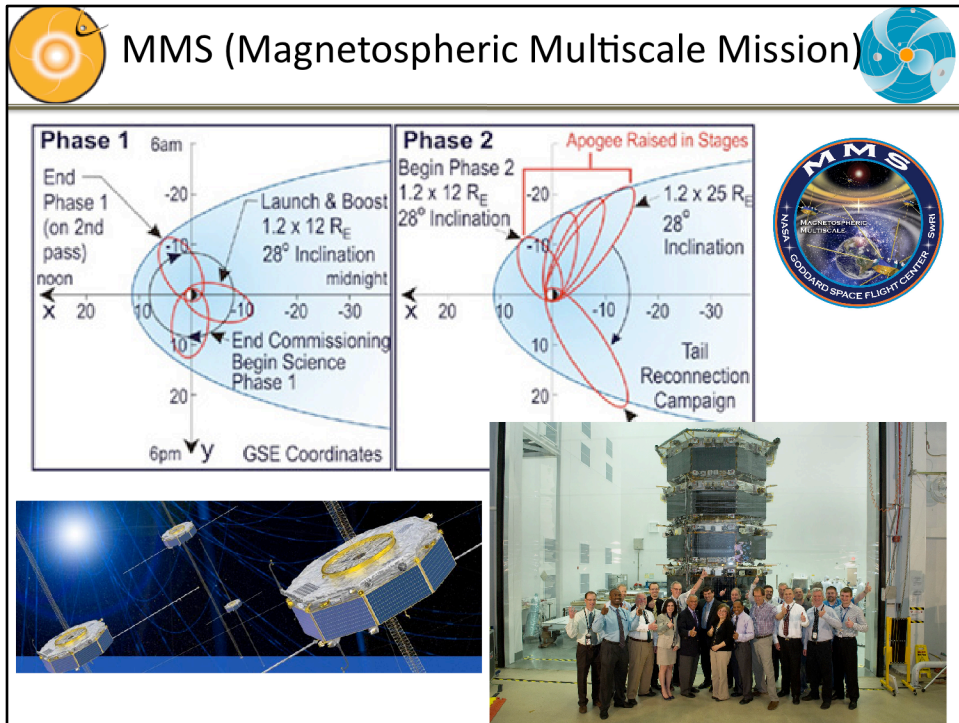
Different observing assets in near-Earth environment



Van Allen Probes



Two Spacecraft In an Elliptical Orbit



<http://mms.space.swri.edu/mission-2.html>



Other types of orbits

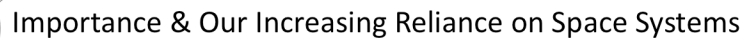


Heliocentric orbit: An orbit around the Sun.

STEREO A and STEREO B

Interplanetary space

At different planets





Space Weather impacts on spacecraft operation

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Space Environment & Effects (1)



Mechanism	Effect	Source
Total Ionizing Dose (TID)	<ul style="list-style-type: none">• Degradation of microelectronics	<ul style="list-style-type: none">• <i>Trapped protons</i>• <i>Trapped electrons</i>• <i>Solar protons</i>
Displacement Damage Dose (DDD)	<ul style="list-style-type: none">• Degradation of optical components and some electronics• Degradation of solar cells	<ul style="list-style-type: none">• <i>Trapped protons</i>• <i>Trapped electrons</i>• <i>Solar protons</i>• <i>Neutrons</i>
Single-Event Effects (SEE)	<ul style="list-style-type: none">• Data corruption• Noise on images• System shutdowns• Electronic component damage	<ul style="list-style-type: none">• <i>GCR heavy ions</i>• <i>Solar protons and heavy ions</i>• <i>Trapped protons</i>• <i>Neutrons</i>
Surface Erosion	<ul style="list-style-type: none">• Degradation of thermal, electrical, optical properties• Degradation of structural integrity	<ul style="list-style-type: none">• <i>Particle radiation</i>• <i>Ultraviolet</i>• <i>Atomic oxygen</i>• <i>Micrometeoroids</i>• <i>Contamination</i>



UNCLASSIFIED

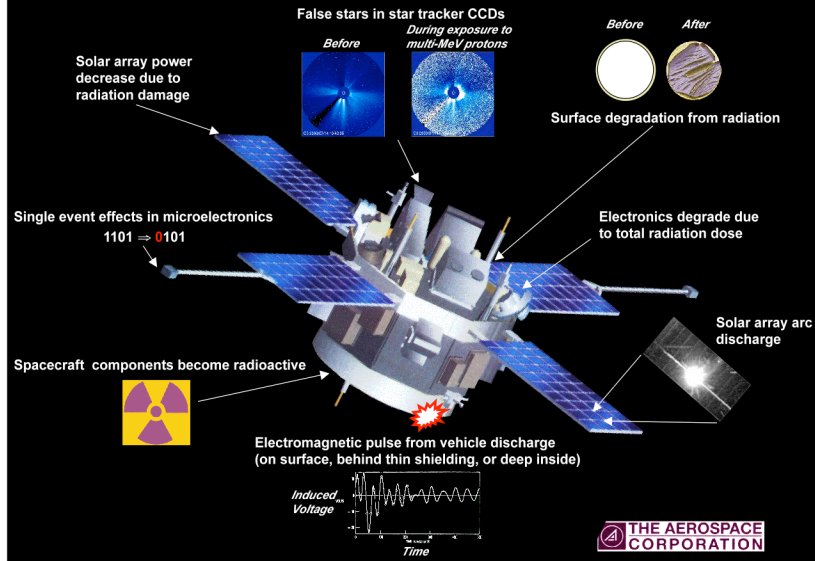


Space Environment & Effects (2)

Mechanism	Effect	Source
Surface Charging	<ul style="list-style-type: none">• Biasing of instrument readings• Power drains• Physical damage	<ul style="list-style-type: none">• <i>Dense, cold plasma</i>• <i>Hot plasma</i>
Deep Dielectric Charging	<ul style="list-style-type: none">• Biasing of instrument readings• Electrical discharges causing physical damage	<ul style="list-style-type: none">• <i>High-energy electrons</i>
Structure Impacts	<ul style="list-style-type: none">• Structural damage• Decompression	<ul style="list-style-type: none">• <i>Micrometeoroids</i>• <i>Orbital debris</i>
Drag	<ul style="list-style-type: none">• Torques• Orbital decay	<ul style="list-style-type: none">• <i>Neutral thermosphere</i>



Major Space Environment Hazards





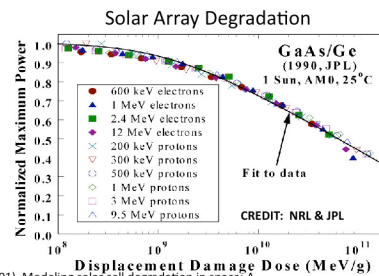
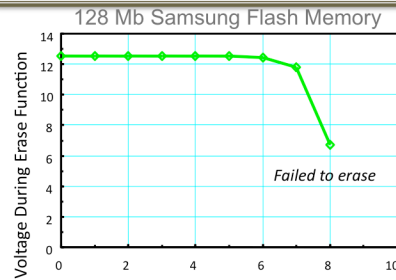
Total Dose Effects



- Total Ionizing Dose (TID) – cumulative damage resulting from ionization (electron-hole pair formation) causing
 - Threshold voltage shifts
 - Timing skews
 - Leakage currents
- Displacement Damage Dose (DDD) – cumulative damage resulting from displacement of atoms in semiconductor lattice structure causing:
 - Carrier lifetime shortening
 - Mobility degradation

DDD can also be referred to in the context of Non-Ionizing Energy Loss (NIEL)

Messenger, S. R., Summers, G. P., Burke, E. A., Walters, R. J. and Xapsos, M. A. (2001), Modeling solar cell degradation in space: A comparison of the NRL displacement damage dose and the JPL equivalent fluence approaches. Prog. Photovolt: Res. Appl., 9: 103–121. doi: 10.1002/pip.357



Messenger, S. R., Summers, G. P., Burke, E. A., Walters, R. J. and Xapsos, M. A. (2001), Modeling solar cell degradation in space: A comparison of the NRL displacement damage dose and the JPL equivalent fluence approaches. Prog. Photovolt: Res. Appl., 9: 103–121. doi: 10.1002/pip.357



Seven types SWx impacts for NASA's robotic missions



1. **Spacecraft surface charging caused by low-energy (< 100 keV) electrons**, which are abundant, for example, in the inner magnetosphere during magnetospheric substorms.
2. **Spacecraft internal electrostatic discharge caused by high-energy electrons (> 100 keV)** that exist, for example, in the dynamic outer radiation belt of the Earth.
3. **Single event effects due to high-energy (> 10 MeV) protons and heavier ions** generated, for example, in solar flares and in coronal mass ejection (CME) shock fronts.
4. **Total dosage effects caused by cumulative charged particle radiation** received by spacecraft.
5. **Increased spacecraft drag caused by the thermal expansion of the Earth's upper atmosphere** during space weather storms.
6. **Communication disruptions between ground stations and spacecraft** due to ionospheric irregularities.
7. **Attitude control disruptions caused, for example, by large storm-time magnetic field fluctuations** in the geostationary orbit.

Feedback from our annual SWx workshop for robotic missions



Space weather impacts on sc (cont'd)



- low-energy protons (< 10 MeV) pose a problem due to trapping into charge-coupled device (CCD) substrates.
- ➔ virtually any part of electron and ion spectra ranging from low to relativistic energies can impact spacecraft operations.



Space Environment Anomalies



- According to a study by the Aerospace Corporation the **2 most common types of spacecraft anomalies by far are due to electrostatic discharge (ESD) and single event effects (SEE)**
- Reported results*:

Anomaly Type:	Number of Occurrences:
ESD	162
SEE	85
Total Dose and Damage	16
Miscellaneous	36

* H.C. Koons et al., 6th Spacecraft Technology Conference, AFRL-VS-TR-20001578, Sept. 2000



Surface Charging



Surface charging: which can lead to electrostatic discharges (ESD),

ESD: can lead to a variety of problems, including component failure and phantom commands in spacecraft electronics [Purvis et al., 1984].

Purvis, C. K., H. B. Garrett, A. C. Wittlesey, and N. J. Stevens (1984), Design guidelines for assessing and controlling spacecraft charging effects, NASA Tech. Pap. 2361

<https://standards.nasa.gov/documents/detail/3314877>



Surface Charging



Commercial satellite anomaly

Substorm injections (Aurora)

More often in the midnight to morning sector

<100 keV e- distribution: similar behavior as spacecraft anomalies

=> Surface charging might be the main cause of the anomalies.

Choi, H.-S., J. Lee, K.-S. Cho, Y.-S. Kwak, I.-H. Cho, Y.-D. Park, Y.-H. Kim, D. N. Baker, G. D. Reeves, and D.-K. Lee (2011), Analysis of GEO spacecraft anomalies: Space weather relationships, Space Weather, 9, S06001, doi:10.1029/2010SW000597.



Surface Charging Hazards distribution

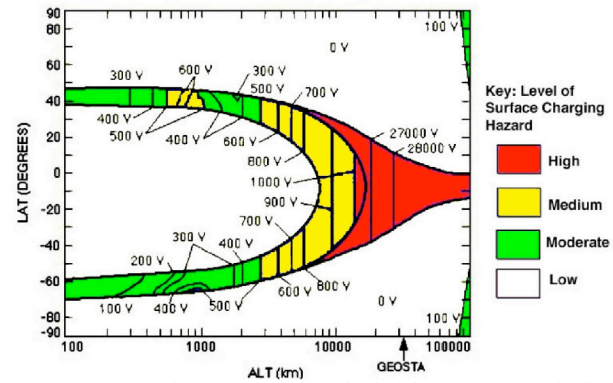


Figure 1—Earth Regimes of Concern for On-Orbit Surface Charging Hazards for Spacecraft Passing Through Indicated Latitude and Altitude (Evans and others (1989))



Title: Mitigating In-Space Charging Effects-A
Guideline

Document Date: 2011-03-03

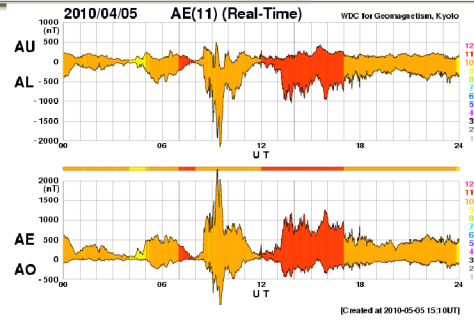
Revalid and Reaffirmed Date: 2016-03-03

Revision: A

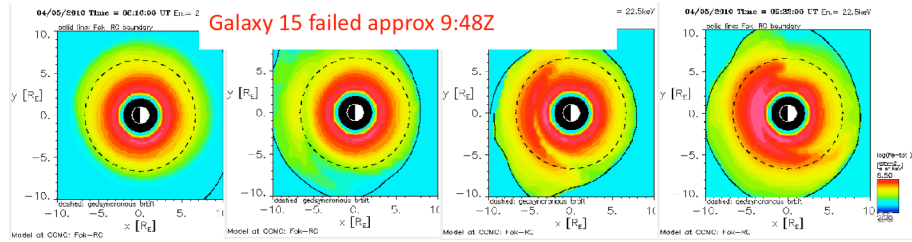
Organization: NASA



Galaxy 15 failure on April 5, 2010 - surface charging might play a role



22keV electrons 4/5, 8:16-9:32Z





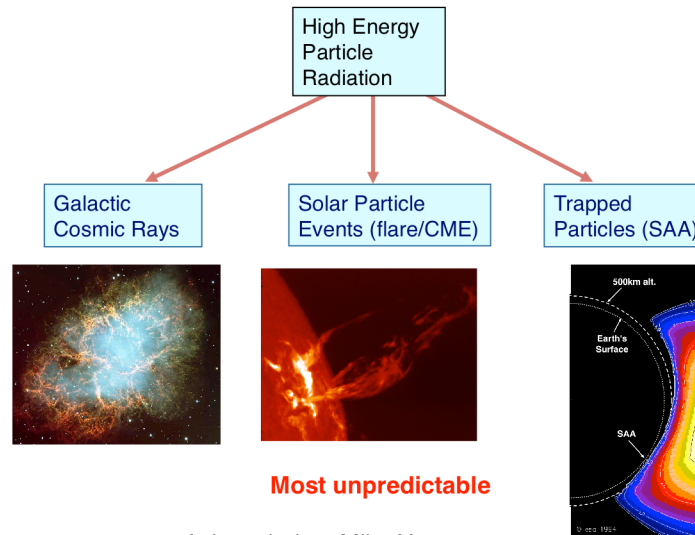
Environmental Source of SEE (single event effects)



- Single Event Environments in Space
 - Galactic Cosmic Rays
 - Solar Particle Events (flare/CME)
 - Trapped Protons in the inner belt (1 – 3 RE)
 - High energy neutrons



SEE source in Space



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Acknowledge: Mike Xapsos



Galactic Cosmic Rays



- Galactic cosmic rays (GCR) are high-energy charged particles that originate outside our solar system.
- Supernova explosions are a significant source

Anticorrelation with
solar activity
More pronounced/
intense during solar
minimum

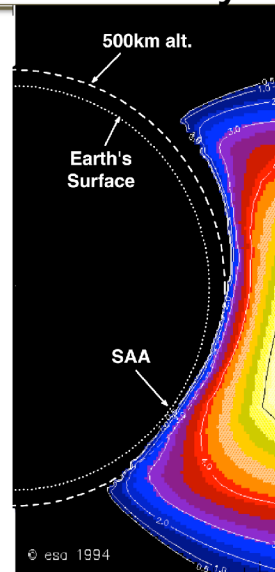




South Atlantic Anomaly



- Dominates the radiation environment for altitudes less than about 1000 km.
- Caused by tilt and shift of geomagnetic axis relative to rotational axis.
- Inner edge of proton belt is at lower altitudes south and east of Brazil.

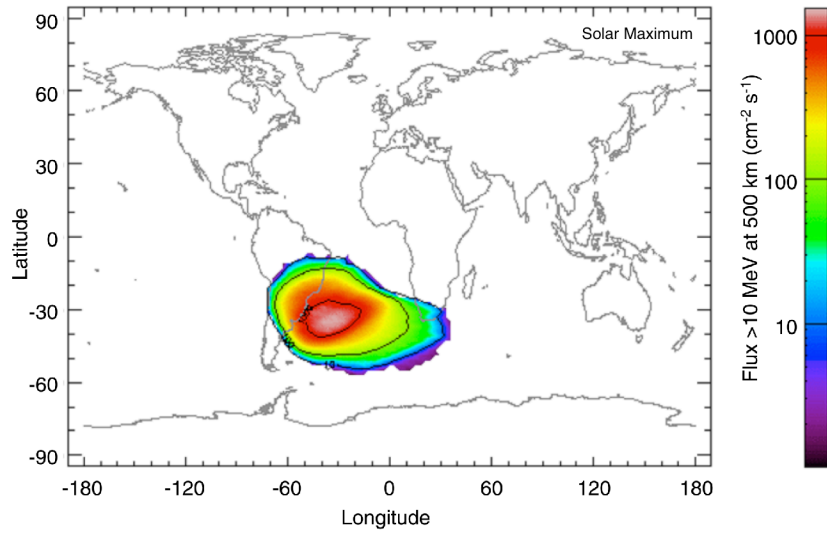


E.J. Daly et al., IEEE TNS, April 1996

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South Atlantic Anomaly



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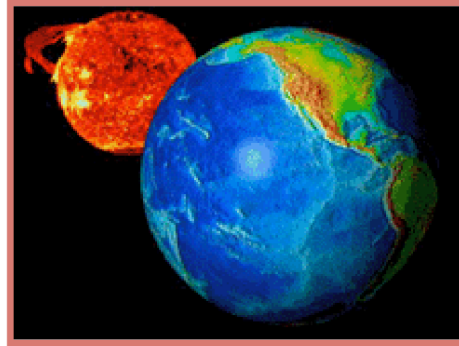
From SPENVIS, <http://www.spenvis.oma.be/>



Solar Particle Events



- Caused by flare/CME

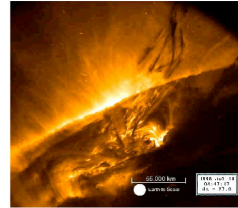
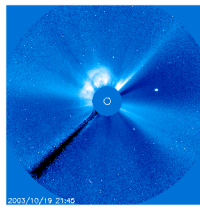
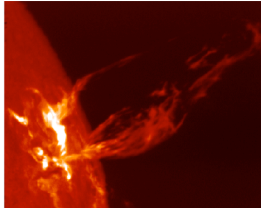




Characteristics of SEPs



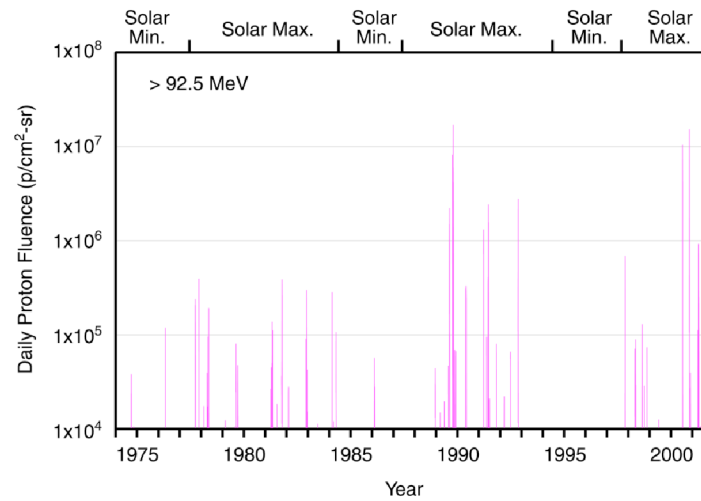
- Elemental composition* (may vary event by event)
 - 96.4% protons
 - 3.5% alpha particles
 - 0.1% heavier ions (not to be neglected!)
- Energies: up to \sim GeV/nucleon
- Event magnitudes:
 - > 10 MeV/nucleon integral fluence: can exceed 10^9 cm^{-2}
 - > 10 MeV/nucleon peak flux: can exceed $10^5 \text{ cm}^{-2}\text{s}^{-1}$



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Solar Cycle Dependence



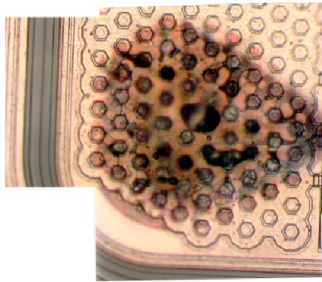
Most unpredictable



What is a Single Event Effect?



- Single Event Effect (SEE) – any measureable effect in a circuit caused by single incident ion
 - Non-destructive – SEU (Single Event Upset), SET (single event transients), MBU (Multiple Bit Upsets), SHE (single-event hard error)
 - Destructive – SEL (single event latchup), SEGR (single event gate rupture), SEB (single event burnout)



*Destructive event
in a COTS 120V
DC-DC Converter*



Single Event Upsets



- SEUs: are soft errors, and non-destructive. They normally appear as transient pulses in logic or support circuitry, or as bitflips in memory cells or registers.



Destructive SEEs



- Several types of hard errors, potentially destructive, can appear:
- Single Event Latchup (SEL) results in a high operating current, above device specifications, and must be cleared by a power reset.
- Other hard errors include Burnout of power MOSFETS (Metal Oxide Semiconductor Field-Effect Transistor) , Gate Rupture, frozen bits, and noise in CCDs.



Anomalies March 2012 SWx events SEEs dominate



- Quite a few NASA spacecraft experienced anomalies, majority of which are SEEs. Some of them required reset/reboot.

Details to be discussed later.

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Internal Charging

- energetic electrons in the outer radiation belt

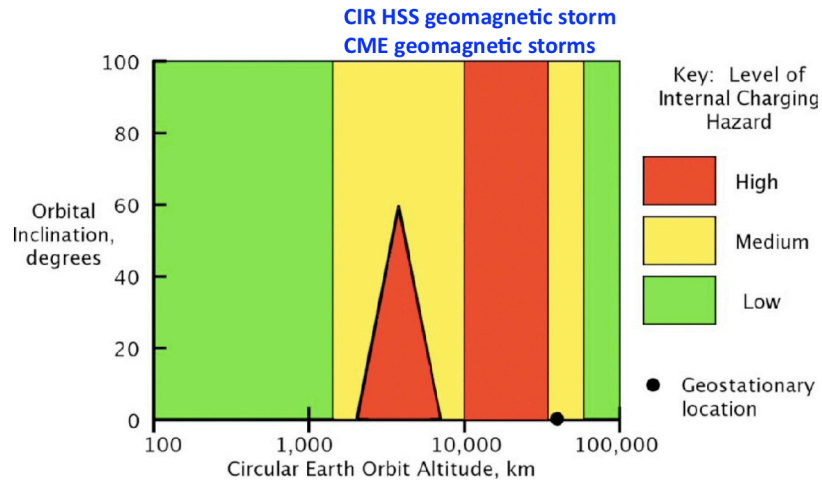


Figure 2—Earth Regimes of Concern for On-Orbit Internal Charging Hazards for Spacecraft with Circular Orbits



Human Safety in Space



- GCR
- **SEP**

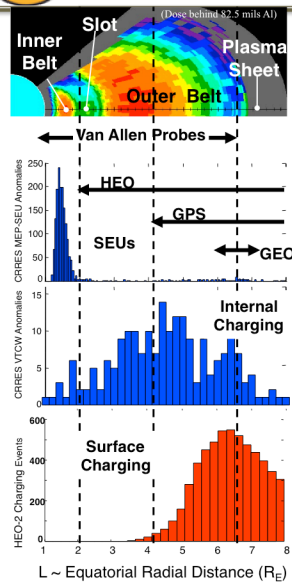
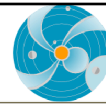
Johnson Space Center/Space Radiation
Analysis Group (SRAG)

Limit: the > 100 MeV flux exceeding 1pfu
(1 pfu = 1 particle flux unit = $1/\text{cm}^2/\text{sec}/\text{sr}$)

- All clear (EVA –extravehicular activity)



Space Environment Hazards (different types of charging) for Spacecraft in the near-Earth environment

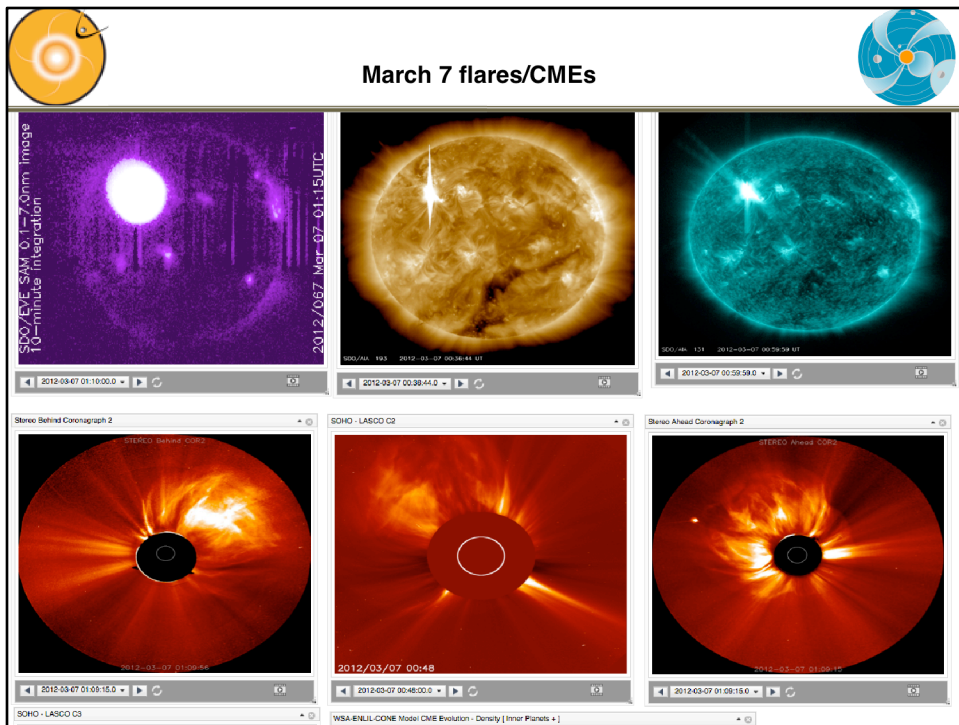


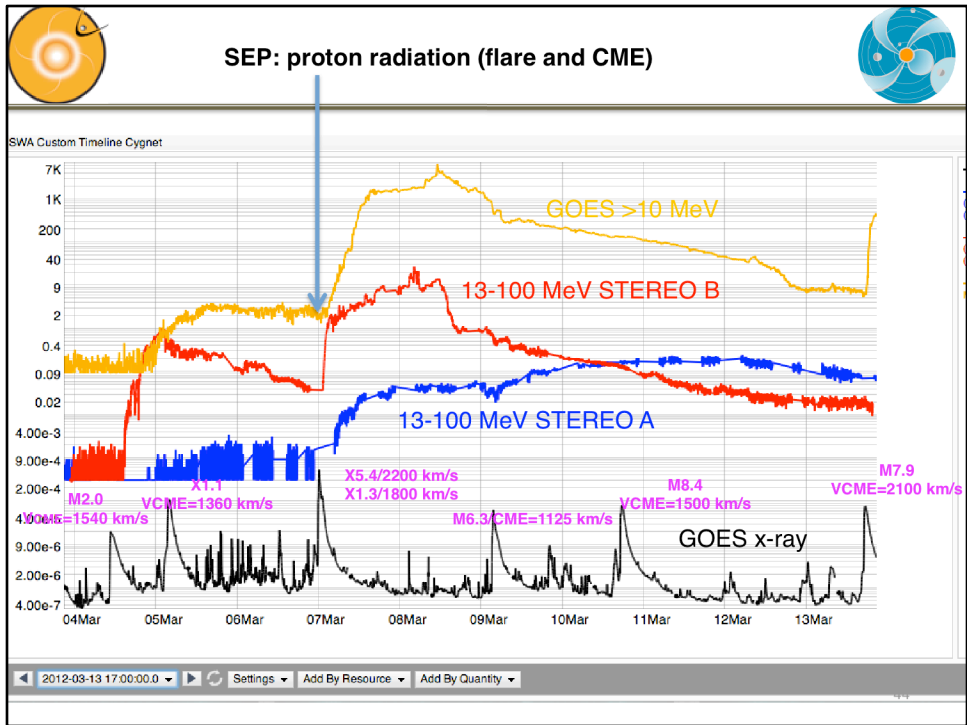
- Single Event Effects tend to occur in the inner (proton) belt and at higher L shells when a solar particle event is in progress.
- Internal electrostatic discharges (ESD) occur over a broad range of L values corresponding to the outer belt, where penetrating electron fluxes are high (300 keV – few MeV electrons)
- Surface ESD tends to occur when the spacecraft or surface potential is elevated: at 2000-0800 local time in the plasma sheet and in regions of intense field-aligned currents (auroral zone) (few eV – 50 keV) - plasma sheet, ring current, aurora zone, magnetosheath
- Event Total Dose occurs primarily in orbits that rarely see trapped protons in the 1-20 MeV range (e.g., GEO, GPS) because these are the orbits for which solar particle events and transient belts make up a majority of the proton dose (including displacement damage)

Courtesy: Paul O'Brien



Operator response to SWx impacts
spacecraft specific/instrument specific





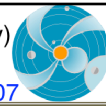


Major events from the long- lasting AR1429 during March 4 – 28, 2012

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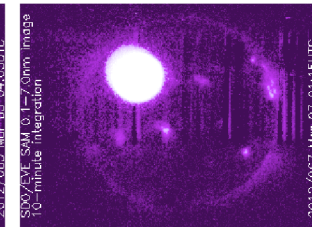
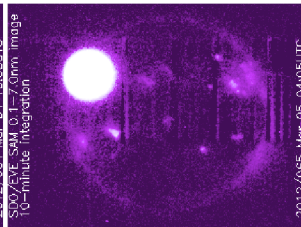
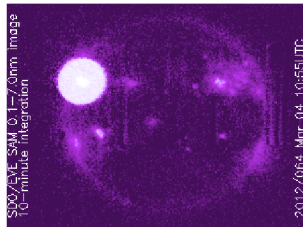
Flares of the Major Earth-Facing Events viewed by SDO EVE (x-ray)



M2.0, 2012-03-04

X1.1, 2012-03-05

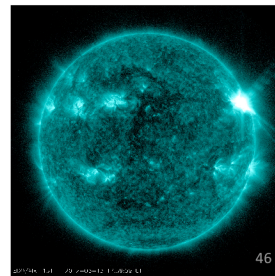
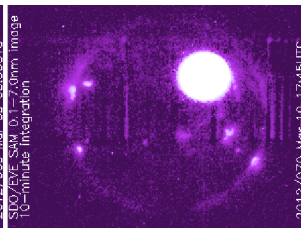
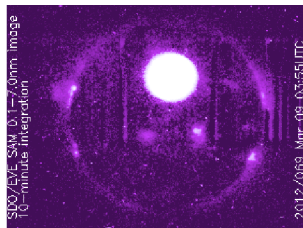
X5.4/X1.3 2012-03-07



M6.3, 2012-03-09

M8.4, 2012-03-10

M7.9, 2012-03-13





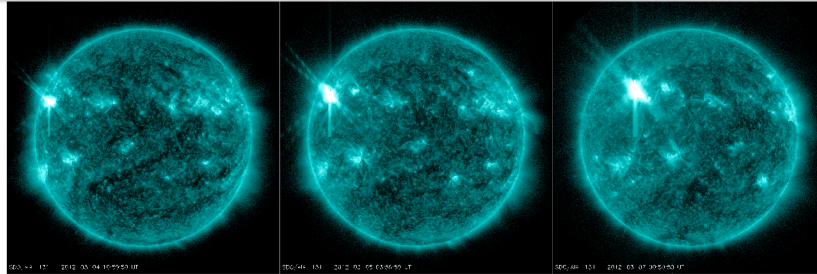
Flares of the Major Earth-Facing Events viewed by SDO AIA 131



M2.0, 2012-03-04

X1.1, 2012-03-05

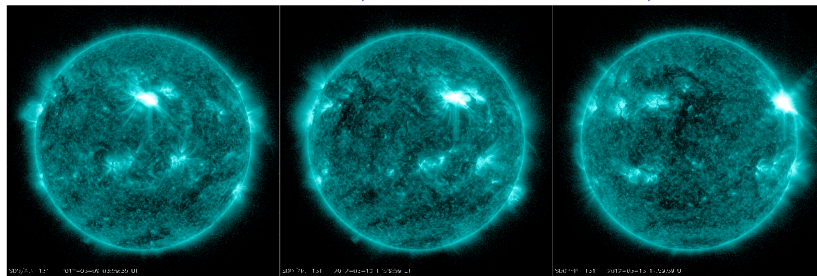
X5.4/X1.3 2012-03-07

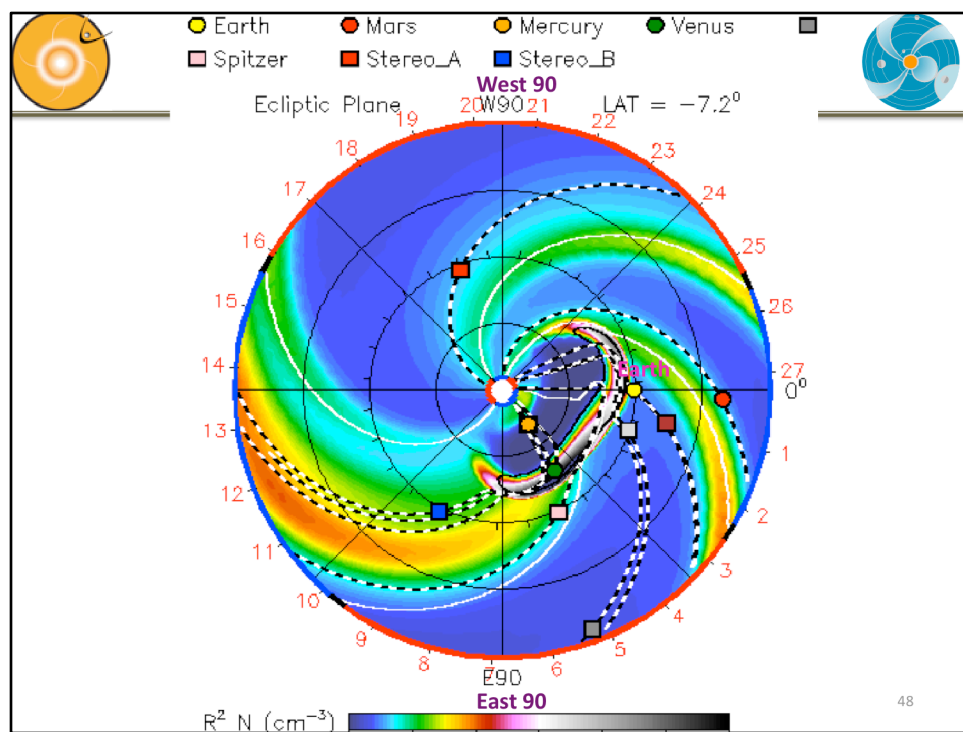


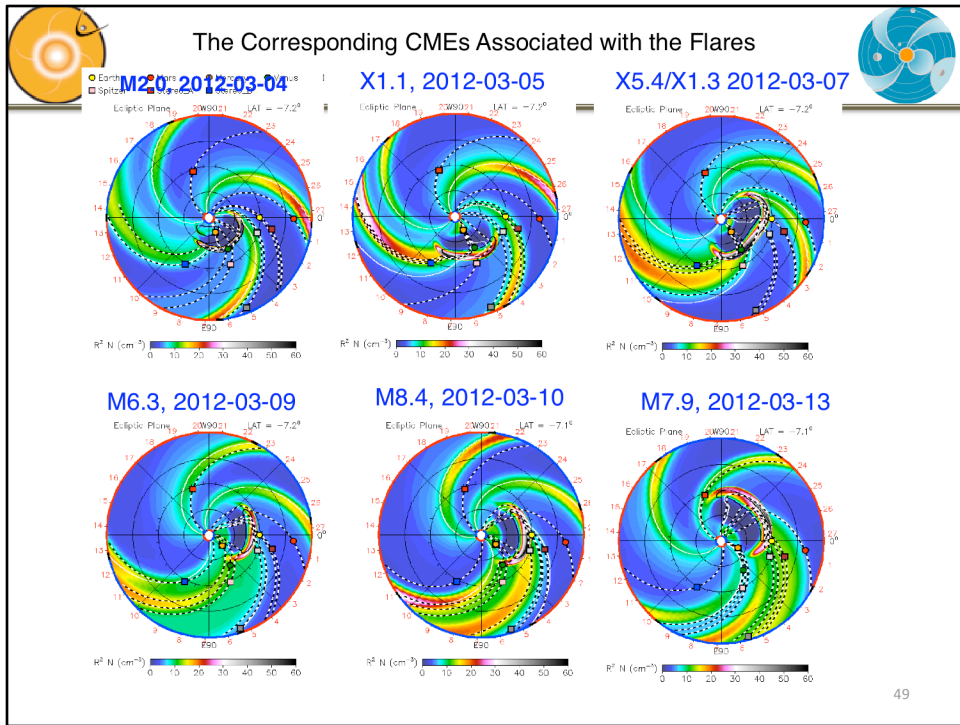
M6.3, 2012-03-09

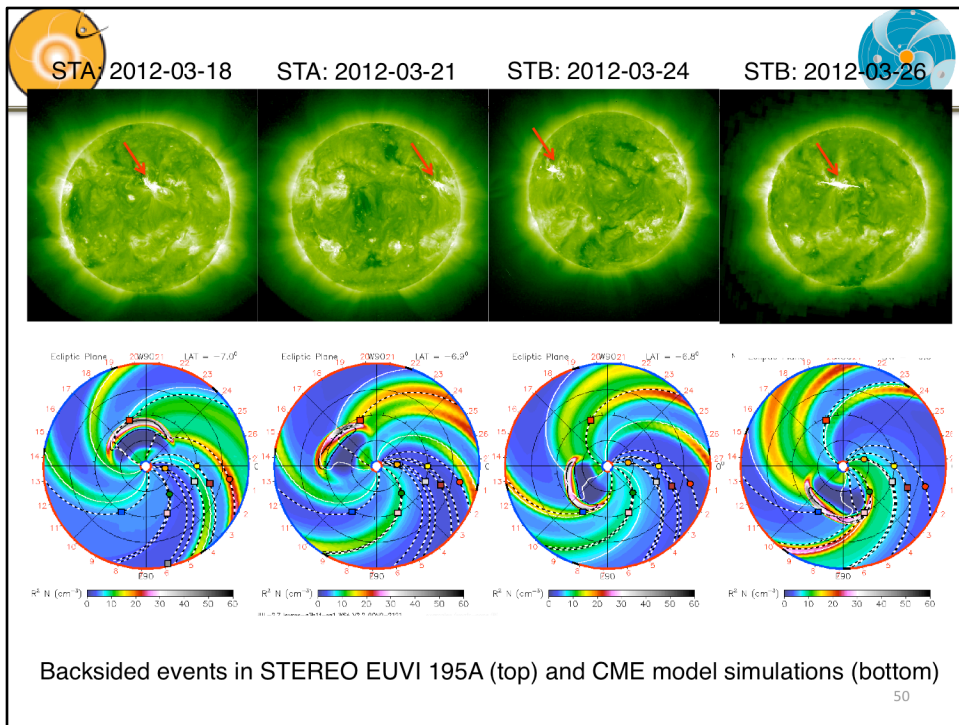
M8.4, 2012-03-10

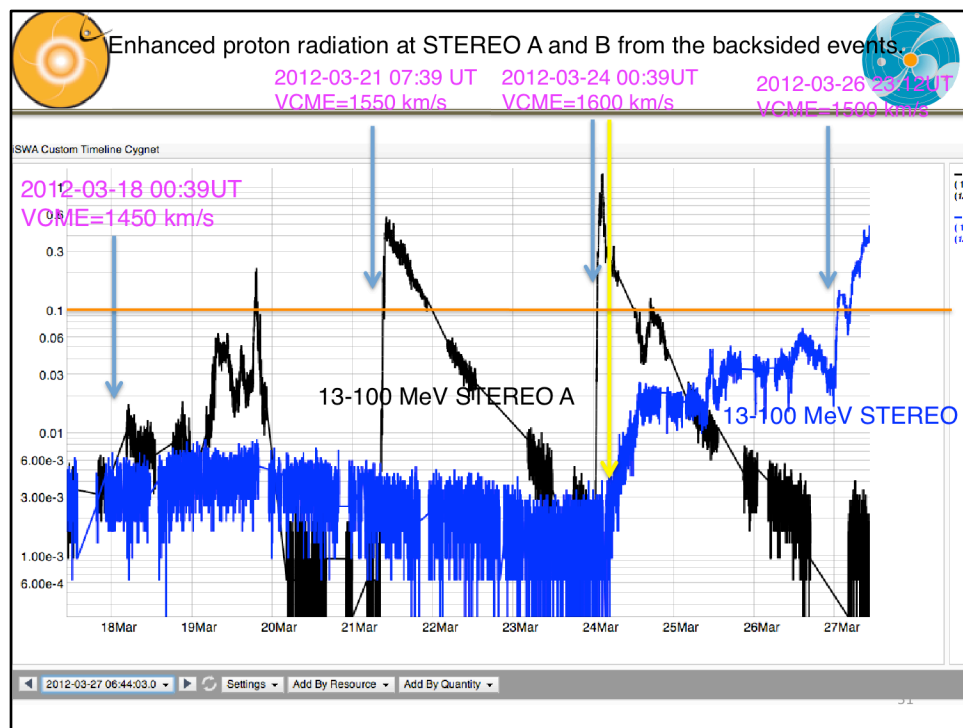
M7.9, 2012-03-13











Enhanced proton radiation at STEREO A and B from the backside events.



Supplementary Material/contact info



- View our video, Incredible Active Region 1429: One for the record books, to learn more about the activities from this region from March 4 – March 28, 2012. <http://youtu.be/PbyJswbX4VA>
- This video has been updated at the following link: <http://youtu.be/dxI5drPY8xQ>
(And also available on <http://vimeo.com/nasaswc/ar1429>)
- Summary Video of the March 7, 2012 event
<http://youtu.be/HeoKf6NfEJI>
Full text of event summary
<http://goo.gl/dTnfd>

NASA Space Weather Center
<http://swc.gsfc.nasa.gov/main/>



Supplementary material



- Youtube video from Henry Garrett at JPL -
<http://www.youtube.com/watch?v=NarzGDuYYX4>

2 hour and 40 minutes long

KSC Space weather training materials

http://ccmc.gsfc.nasa.gov/support/SWREDI/training_ksc/